Modern Concepts of Cardiovascular Disease

Published monthly by the AMERICAN HEART ASSOCIATION

1790 BROADWAY AT 58TH STREET, NEW YORK, N. Y.

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VOL. XV OCTOBER, 1946 NO. 10

THE COLLATERAL CIRCULATION OF THE HUMAN HEART

Despite the accumulation of considerable material on the coronary circulation during the past two hundred and fifty years, many questions still remain to be answered. It is our purpose to review briefly some of the problems concerning the collateral circulation of normal and diseased human hearts with emphasis on anatomical considerations.

Although it was in 1708 that Thebesius, by careful dissection, first demonstrated the occurrence of anastomoses between both coronary arteries, the existence of intercoronary arterial anastomoses in normal hearts has been a point of dispute up to the present time. There have been two sharply divergent opinions about this question. There are those whose investigations have led to the conclusion that the coronary arteries in normal hearts are end-arteries, and that the only anastomoses between branches of the coronary arteries are via the capillaries. Hyrtl in 1855, on the basis of injection and corrosion experiments, denied the existence of coronary arterial anastomoses, and in 1866 Henle confirmed his work. Cohnheim and von Schulthess-Rechberg in 1881, as the result of their experiments on the clamping of coronary arteries in curarized dogs, stated that the coronary arteries were end-arteries. In 1940 Blumgart, Schlesinger and Davis, utilizing their lead-agar injection technic, stated that anastomoses larger than 40 micra in diameter are not found in normal hearts, and that these fine intercoronary communications are not of functional significance in obviating the untoward results of rapidly developing coronary narrowing or occlusion.

On the other hand, a great body of evidence supporting the existence of intercoronary arterial anastomoses has been accumulated by many investigators, culminating in the classical anatomic studies of Spalteholz and of Gross. Employing methods consisting of the injection of colored or radiopaque gelatin solutions into the coronary arteries, with clearing of the remaining tissues followed by dissection and roentgenography of the intact heart, Spalteholz in 1907 and Gross in 1921 reached the following conclusions: (1) No end-arteries exist in the heart; (2) anastomoses exist between the right and left coronary arteries both in their capillary as well as precapillary distribution; (3) anastomoses exist between the branches of each coronary artery; (4) anastomoses exist between the coronary arteries and vessels from the adjacent and attached organs; (5) anastomoses in the heart are universal and abundant. Furthermore, these observers felt that coronary anastomoses increased with age. Gross emphasized the increasing development of septal anastomoses and rami telae adiposae (vessels lying in the fatty tissue under the visceral pericardium), beginning in the second decade of life and reaching its maximal development in the seventh decade of life.

Following these investigations, the question of interarterial coronary anastomoses apparently was settled until Blumgart, Schlesinger and Davis published their brilliant and painstaking studies on the coronary circulation of normal and pathologic hearts in 1940. Their method of study, developed by Schlesinger in 1938, consisted of the injection of a radiopaque lead-agar mass into the coronary arteries followed by unrolling of the heart so that all of the coronary arteries could be visualized in one plane by roentgenography. Then, the filled coronary tree was carefully dissected with the aid of an x-ray of the radiopaque vessels. The lead-agar perfusate regularly penetrated to all vessels 40 micra in diameter, reached about 50 per cent of vessels 20 micra in diameter and never injected vessels smaller than 10 micra in diameter. When this material was injected into one of the coronary arteries, they were unable to demonstrate its presence in the opposite coronary artery in normal hearts. They therefore concluded that intercoronary anastomoses larger than 40 micra in diameter are not found, and that anastomotic communications measuring less than approximately 40 micra in diameter exist between the coronary arteries of normal hearts. However, in regard to pathologic hearts their conclusions were as follows: "Obstruction to normal coronary arterial blood flow by arteriosclerotic narrowing or occlusion regularly results in the development of intercoronary anastomoses measuring 40 to 200 micra in diameter. Anastomotic circulation develops, then, only when and where it is needed. The development of such anastomoses is not related to age, for they are not present in the hearts of even senile patients when little or no coronary arteriosclerosis is present." Another significant conclusion was that anastomoses over 40 micra in diameter occurred in hypertrophied hearts even in the absence of coronary artery disease.

In this laboratory we have been interested in determining quantitatively the volume of coronary collateral flow, and the size of the lumina of anastomotic channels in human hearts. In 1942, Prinzmetal, Kayland, Margoles and Tragerman published a quantitative method for determining collateral coronary circulation in human hearts obtained at necropsy. Adapting Dock's kerosene perfusion method, kerosene was perfused through both coronary arteries under constant pressure, and the flow through each artery was measured. Then, one of the coronary arteries was suddenly occluded by clamping the cannula, and the flow through the opposite coronary artery was mentioned. If the flow through the unobstructed vessel increased, then it would seem that the increase in flow must necessarily be due to fluid going through the collateral circulation. That is, the increase in the volume of fluid flowing through the unobstructed coronary artery represents that amount of fluid flowing into the vascular tree of the opposite side of the heart distal to the occluded coronary artery, via the available anastomotic channels present. In this way then the percentage of collateral circulation can be measured. Collateral circulation, averaging 4.16 per cent, was found in all but one of twelve normal human hearts. The average collateral flow from the left to the right coronary artery was

19.2 c.c. per minute or 4.55 per cent of the flow through the left coronary artery, while the average flow from the right to the left coronary artery was 6.2 c.c. per minute or 4.05 per cent of the flow through the right coronary artery.

In 1942 these investigators also found that if a radiopaque gelatin mixture with a viscosity slightly greater than blood (employed by Dock) was injected into one coronary artery of normal hearts of persons ranging from three to sixty-seven years of age, it regularly appeared at the opposite coronary artery. The entire coronary arterial tree was filled as was demonstrated by roentgenography. If this same radiopaque substance was injected into either the anterior descending or the circumflex branch of the left coronary artery, the entire coronary arterial tree was filled.

More recently, Prinzmetal, Bergman, Simkin and Kruger, in studies to be published, have been able to measure quantitatively the size of the lumina of these anastomotic channels by means of a new method of study. Glass spheres, ranging from 10 to 440 micra in size and suspended in Dock's radiopaque mixture, were injected into one of the coronary arteries under physiologic pressure and, as a result, glass spheres were recovered from the opposite coronary artery, the coronary sinus and the ventricular cavities. Thus far twelve hearts, obtained from patients ranging from six to seventy-five years of age, have been injected by this means. The coronary arteries of these hearts were normal or exhibited only a minimal degree of arteriosclerosis. Glass spheres were obtained from the opposite coronary artery in all but two instances. These beads were measured microscopically by means of a calibrated reticule. In all instances the largest spheres recovered from the opposite coronary artery measured 70 to 80 micra in diameter, thus indicating that channels of arteriolar dimensions were present between the right and left coronary arteries. There were no variations with age, these findings being uniform at all ages. In preliminary work on hearts with severe coronary arteriosclerosis or with ventricular hypertrophy, larger beads were recovered from the opposite coronary artery, the maximal size ranging from 130 to 150 micra in diameter. Thus, in pathologic hearts our findings so far are in substantial agreement with those of Blumgart, Schlesinger and Davis.

We also have employed another method of study to demonstrate the existence of interarterial anastomoses in the normal human heart because all previous technics involved the use of nonphysiologic media. Human red cells, rendered radioactive by incubation with radioactive phosphorus (P^{32}), were perfused through either the anterior descending branch or the circumflex branch of the left coronary artery at a pressure of 100 mm. of mercury. The heart was then unrolled in the manner described by Schlesinger and the distribution of the radioactive red cells was determined by means of (1) Geiger counts at various arbitrarily chosen areas on the endocardial and pericardial surfaces, and (2) by exposing the heart to x-ray film for twenty-four to forty-eight hours, thus obtaining a radio-autograph. We were able to show that the entire left ventricle was well filled with blood, thus indicating the presence of abundant arterial anastomoses in the left ventricle. Radioactive red cells also were found in the right ventricle in all these experiments, again demonstrating the existence of collateral channels supplying the right ventricle.

The question of arteriovenous anastomoses in the human heart apparently has been neglected in the past. We have been able to find very few references pertaining to this important subject in the literature. In 1911, Nussbaum described direct connections between arteries and veins made up of a single layer of endothelium, possessing no muscular coats and lying in the subendocardium. He considered these as safety outlets for arterial blood when the pressure becomes too high. Wearn in his discussion of the anatomy of the coronary vessels states the following: "Arteriolar-venous communications also occur in normal hearts. They are infrequently found during a study of serial sections of the myocardium. Because of their rarity, they are probably of little importance." In our studies employing the injection of glass spheres, we have been able regularly to obtain beads from the coronary sinus following injection into the right or left coronary artery. The maximal size of these recovered beads ranged from 80 to 170 micra in diameter in both normal and pathologic hearts. It is quite obvious, then, that channels of larger magnitude than capillaries must exist between the coronary arteries and coronary veins to allow the passage of spheres of such dimensions. The regular occurrence of such arteriovenous anastomoses in all hearts studied raises the question of the possible functional significance of such communications. The question is posed whether or not they supply a mechanism to increase blood flow and provide more efficient regulation of the myocardial circulation. It is not inconceivable that such channels could allow arterial blood to supply the myocardium by (1) direct supply to the capillary bed, and (2) a shunt into the coronary veins which are connected with thebesian vessels and capillaries. Thus, it is theoretically possible for ventricular muscle to get oxygenated blood through arteriovenous anastomoses even if a coronary artery is occluded.

One other point of interest concerns the nature of the channels opening directly into the ventricular cavities. Wearn and his associates have described three such groups of vessels: arterioluminal vessels, arteriosinusoidal vessels and thebesian veins. Arterioluminal vessels were described as arising from coronary arteries or arterioles and emptying directly into the ventricular chamber. Wearn stated that their size was of the magnitude of arterioles. He also described branches of small arteries arborizing into myocardial sinusoids of diameters varying from 50 to 250 micra, these being called arteriosinusoidal vessels. Finally, he described thebesian veins which, on the one hand, anastomose with coronary veins and, on the other hand, with the capillary bed. These thebesian veins also communicated with each other as well as directly into the ventricular chambers. In our studies, following injection into one of the coronary arteries, we have been able regularly to recover beads from each ventricular cavity, the beads ranging in size from 100 to 400 micra in diameter. We are unable to tell which of the three groups of channels described by Wearn was traversed, but we can confirm Wearn's opinion as to the size of these communications.

These are but a few of the highlights concerning the intricacies of the collateral circulation of the heart. We hope that we have conveyed the impression that the coronary circulation is far from a dead subject, but rather one about which much remains to be learned both from the anatomic and physiologic points of view.

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